91602
new 82-10

ontario hydro
research division

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part

To: Mr. J.E. Mitchell
Manager,
Technical Services and Development Dept.
Program Support and Services Division
C25 F06

OPERATIONAL TESTING OF TWO THERMAL ENERGY STORAGE FURNACES

N.H. Milligan

ABSTRACT

Two thermal energy storage furnaces were evaluated in the laboratory. One furnace used a low density crushed rock as the storage medium. The other used high density ceramic brick. The furnaces were tested to determine standby heat loss, operating efficiencies, and safety. The crushed rock furnace performed reliably with standby losses ranging from 2.8 to 3.3 kW and an operating efficiency of 79%. The main deficiencies recorded during the test were: the operating storage capacity and heat output. The ceramic brick furnace had standby losses ranging from 2.5 to 3.1 kW and an operating efficiency of 70%. This furnace failed to operate satisfactorily due to overheating of a control panel that caused plenum surface temperature to reach 117°C. This surface temperature represents a safety hazard.

INTRODUCTION

Thermal energy storage (TES) is a practical method of shifting on-peak load to off-peak hours. One of the most convenient and largest loads available for shifting, in the residential sector, is space heating. The average electrically heated home has 10-15 kilowatts (kW) of installed heating capacity. The diversified load of approximately 8 kW can be shifted to off-peak periods using suitable thermal storage furnaces.

All residential TES furnaces use a storage medium of some type to store sufficient sensible heat for off-peak heating. Ontario Hydro, through the Technical Services and Development and Program Testing and Analysis Departments have identified two commercially available furnaces which are of interest from an energy management perspective. The furnaces differ primarily in the medium used to store heat. The two furnaces represent a trade-off in size, cost and operating temperatures.

job	file	date	report no.
12-123	814.343	November 10, 1989	89-274-X

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

One furnace, referred to as the **crushed rock furnace**, uses a low density, low heat capacity rock to store heat at moderate temperatures. The second furnace, referred to as the **ceramic brick furnace**, uses a high density, high heat capacity brick, to store heat at relatively high temperatures.

Each of these furnaces was evaluated in a series of operational tests. Basic performance parameters and operating characteristics were determined. The furnaces were also evaluated qualitatively for construction, design, and reliability.

This report describes the test procedures used and the corresponding test results. Recommendations on each furnace, as to its inclusion in an energy management program, are given. The report discusses each furnace independently, and presents results first for the crushed rock and second for the ceramic brick.

RESULTS

1.0 Crushed Rock Furnace

A description of the crushed rock furnace, including a schematic diagram, is given in Appendix A. Modes of operation are also described. A series of tests was run to measure static and dynamic characteristics. The tests are listed and described in Appendix B. Table 1 summarizes the results of the standby loss tests.

Table 1
Standby Loss Tests

standby loss with fan	3.3 kW
standby loss without fan	2.8 kW
charge/discharge	1.2 kW

The difference between the results of the standby tests with the fan on and with the fan off, measures the heat loss due to air leakage through the furnace (damper and storage section). The unwanted heat loss is relatively small, 0.5 kW. This is due to the low permeability of the rock storage, which restricts the airflow through the furnace, caused by the house fan. The lower standby loss during the charge/discharge test is due to lower average temperature of the storage medium during the 24 hour cycle.

Table 2 summarizes the charge/discharge test results. The total electrical energy input was 133 kWh per day. Total energy recovered as heat was 105 kWh per day. This gives a net efficiency of 79%.

Safety limit tests showed that the furnace operated in a safe and consistent manner. The control logic worked correctly in all cases.

The maximum surface temperatures were measured with the storage chamber fully charged. The highest temperature was 72 °C, recorded at the centre of the top of the chamber. Temperatures on the sides of the chamber ranged from a high of 68 °C at or near the top, to 26 °C at floor level.

Table 2

Charge/Discharge Test

electrical energy input	266 kWh
heat output	209 kWh
test duration	48 hours
average supply air temperature	40 °C
minimum supply air temperature	33 °C
maximum storage temperature	375 °C
maximum operating power delivery*	7.5 kW

* *delivered to the space heating system of the house*

Qualitative Observations and Analysis

The success of any TES program is dependent on more than just the technical specifications of a furnace. All TES furnaces must be judged against the standards for space heating equipment in general. This includes: cost, maintenance, reliability and customer satisfaction.

The crushed rock furnace was designed to be a low cost TES alternative. This is true of capital cost. However, based on the amount of effort required to assemble the furnace in the laboratory, it is estimated that the furnace will require a minimum of two man-days to assemble in the field.

The installation of the furnace entails the fitting together of many pieces, the tightening of many bolts, the handling of approximately 1800 kg of rock, and 20 bags of vermiculite. All this work must be done in a customer's home under varying conditions. The critical dimension of the furnace is the height. A basement with a minimum ceiling height of 2.44 m (96 in) is required to efficiently assemble this furnace.

The furnace went together relatively easily; all the parts were supplied. The most difficult aspect of the assembly was the filling of the rock. The rock comes in 30 kg bags, which must be emptied into the storage chamber. This would be extremely difficult with limited clearance between the top of the furnace and the ceiling.

The furnace operated reliably during testing. No component failures were recorded. However, two major deficiencies of the furnace were noted: the operating storage capacity and the rate of heat recovery which implicitly affects the heat output. The furnace is rated at 190 kWh storage, with an installed heater power of 24 kW. On an eight-hour off-peak/16-hour on-peak schedule the absolute maximum storage capacity is 192 kWh. The average standby loss of 1.2 kW gives a maximum available storage at the end of eight hours of approximately 182 kWh. In practice, the algorithm used to control the heaters limits the maximum energy input. This is due to the manufacturer using a ten-hour charge period, as well as staging the elements on and off during the charge cycle. As a result, although the furnace has the capacity to store 190 kWh the actual storage capacity under test conditions was only 133 kWh. The limiting factors in this case are the installed heating power and the eight-hour off-peak period.

The average supply air temperature of 40 °C is below the design temperature of 55 °C. This lower air temperature is important for two reasons:

- it limits the maximum power delivered to the space heating system to 7.5 kW which may not be sufficient for an average house (approximately 8 kW). The maximum heat recovery from the furnace in 16 hours was 105 kWh.

- the low supply temperature will adversely affect occupant indoor air comfort.

There are two possible causes of the low supply air temperature:

1. The temperature sensor in the plenum is located too close to the storage duct and therefore it may not accurately reflect the mixed air temperature.

2. The permeability of the crushed rock storage is too low. This could prevent the high pressure storage fan from blowing sufficient air through the storage medium and into the plenum to bring the cold return air up to 55 °C.

The dismantling of the crushed rock furnace was more difficult than the assembly. No consideration has been given for the removal of this furnace from a home. The removal entails handling a large amount of dry dusty material, the vermiculite and the crushed rock. Two man-days were required to disassemble the furnace.

2.0 Ceramic Brick Furnace

The same series of tests was run on this furnace as was run on the crushed rock furnace (see Table B.1 for the test program). Table 3 gives the results of the standby loss tests.

Table 3
Standby Loss Tests

standby loss with fan	3.1 kW
standby loss without fan	2.5 kW
charge/discharge	1.8 kW

The difference between the results of the standby tests with and without the fan on is due to the leakage of hot air through the damper and storage section. The circulation air temperature rose on average, 4 °C. This problem was recognized in earlier designs, and is still a problem on this furnace. The lower standby loss during the charge/discharge test is due to the lower average temperature of the storage medium during the 24 hour cycle.

Table 4 summarizes the charge/discharge test results. The actual energy stored by the furnace over a 71 hour test period was 408 kWh. The total recovered energy, as heat, was 284 kWh. This gives a net efficiency of 70%.

Table 4

Charge/Discharge Test

electrical energy input	408 kWh
heat output	284 kWh
test duration	71 hours
average supply air temperature	53 °C
minimum supply air temperature	22 °C
maximum storage temperature	723 °C
maximum operating power delivery	12 kW

The maximum power delivered to the space heating system was 12 kW. This is sufficient to meet the requirements of a standard house. The average supply air temperature was 53 °C. This is close to the recommended supply duct temperature of 55°C for residential applications.

The safety limit tests, **under normal conditions**, showed that the furnace operated in a safe and consistent manner. Maximum surface temperatures on the furnace were measured with the storage section fully charged. This corresponds to an average brick temperature of 723 °C. The highest surface temperature under normal operation, was 65 °C, recorded at the top of the unit. Temperatures on the sides of the unit ranged from 60 °C at the top to 23 °C at floor level. However, under certain failure modes observed in the laboratory, the maximum surface temperature was 117 °C. This surface temperature represents a safety hazard.

Qualitative Observations and Analysis

The ceramic brick furnace was relatively easy to assemble, when compared to the crushed rock. The furnace came in three large pieces: a plenum, a storage chamber and the ceramic bricks. One man-day was required to assemble the furnace, connect it to the duct work, and hook up the electrical service. No problems were encountered in the assembly or initial operation of the furnace.

During several standby loss and charge/discharge tests, the 60-ampere fuses, in the main control box, failed. This did not prevent the furnace from operating, but did result in two problems. First, once a fuse blows, one half of the heater capacity is lost. This prevents the furnace from fully charging during the off-peak period. The furnace cannot then maintain sufficient heat storage to meet typical house heating demand. Second, if for some reason the control logic of the furnace does not operate properly the operating heater elements may run continuously over the charge period, in an effort to raise the storage temperature to the desired level. Consequently, the storage section becomes locally overheated, either at the top or at the bottom, depending on which elements are operating. If the bottom elements remain operational, core temperatures in the bottom half of the storage chamber rise to 880 °C. These high temperatures cause plenum surface temperatures to reach 117 °C, as previously mentioned.

The failure of the 60-ampere fuses was due to overheating of the control box. Removal of the control panel face plate, which exposed the controls and wiring, eliminated the problem. However, in practice, the furnace cannot be operated in this mode for safety reasons.

The storage capacity, heat recovery and standby losses are as specified by the manufacturer. The only deficiency noted in furnace operation was the induced heat loss to the space heating system when continuous fan operation mode is used (see Appendix A). The additional standby loss, due to leakage around the plenum baffle, was 0.6 kW. This heat loss is undesirable for continuous fan operation mode for two reasons. The constant addition of heat into the house will, on warm days, as in Autumn and Spring, cause overheating and loss of occupant comfort. The additional standby loss also reduces available storage capacity of the furnace during the on-peak period.

Both of these problems can be described generically as a lack of control of the heating system. The control over the furnace, is important to customer satisfaction. Newer heating systems are typified by better control and responsiveness to occupant demands. Both TES furnaces are less responsive to heating demand and operating conditions than conventional heating equipment.

CONCLUSIONS

Crushed Rock Furnace

1. Measured storage capacity was 133 kWh, versus the rated 190 kWh with an overall storage efficiency of 79%.

2. Standby losses ranged from 2.8 to 3.3 kW. A total of 0.5 kW of heat is lost to the air stream when the house fan is constantly circulating air. This indicates leakage through the damper and storage section.

3. The average supply air temperature of 40 °C is below the recommended 55 °C for residential installations. The maximum operating power delivery to the space heating system was 7.5 kW. This reduces both the occupant comfort and the ability of the furnace to meet the average house heat demand of approximately 8 kW.

4. The furnace is large and required two man-days to assemble and install in the laboratory. This represents a significant component of overall cost of the furnace in field installation. In addition the height of the furnace will make assembly in a standard basement difficult.

Ceramic Brick Furnace

5. Measured storage capacity was 140 kWh with an overall storage efficiency of 70%.

6. Standby losses ranged from 2.5 to 3.1 kW. A total of 0.6 kW of heat is lost to the air stream when the fan is constantly circulating air. This indicates leakage through the damper and storage section.

7. The average supply temperature was 53 °C, adequate for residential installations. The maximum operating power delivery to the space heating system was 12 kW, properly sized to meet the heat demand of an average house.

8. The furnace suffered several failures due to overheating of the control panel. The corresponding failure modes caused surface temperature to reach 117 °C. This surface temperature represents a safety hazard.

Both the crushed rock and ceramic brick furnace require some additional development work to become a viable alternative for future energy management programs.

Approved by:

A.F. Baljet
Manager
Electrical Research Department

Submitted by:

for N.H. Milligan
Engineer
Utilization Section

Reviewed by:

M. Perlman
Unit Head - Energy Management
Utilization Section

NHM/MP:dmc

APPENDIX A

Furnace Descriptions

Crushed Rock Furnace

The crushed rock furnace is an American design, consisting of a storage chamber, a night heating section (conventional electric furnace), and a fan/mixing plenum. Figure A.1 shows a schematic of the furnace. The storage chamber contains the rock and off-peak heating elements. The night heating section provides heat during off-peak hours while the unit is recharging. The fan/mixing plenum delivers uniformly heated air to the house. Table A.1 gives dimensions, capacities and operating parameters of this furnace.

Table A.1
Crushed Rock Furnace Characteristics

height	1.98 m (78 in)
width	1.22 m (48 in)
weight of rock	1579 kg (3480 lb)
footprint area	1.438 m^2 (15.5 ft^2)
nominal storage capacity	190 kWh
electrical input	24 kW

There are two basic modes of operation:

- **charging**, during off-peak periods
- **discharging**, during on-peak periods.

In the charging mode, air is drawn down through the rock storage chamber by a small high pressure fan at the bottom of the chamber. The air passes over 8 heating elements located at the top of the chamber, where it is heated to 550 °C. Heat is transferred to the rock storage, from the air as it moves through the chamber. The eight resistive heaters supply a total of 24 kW of power.

In the discharge mode, the direction of air circulation through the storage chamber is reversed. Cold air is drawn from the plenum, into the bottom of the furnace. The air passes up through the crushed rock, and is heated. The air then flows out of the storage chamber into the fan/mixing plenum where it is mixed with cool house air. A control system, using the plenum air temperature, varies the amount of hot air from the storage chamber, trying to maintain a constant 55 °C supply air temperature.

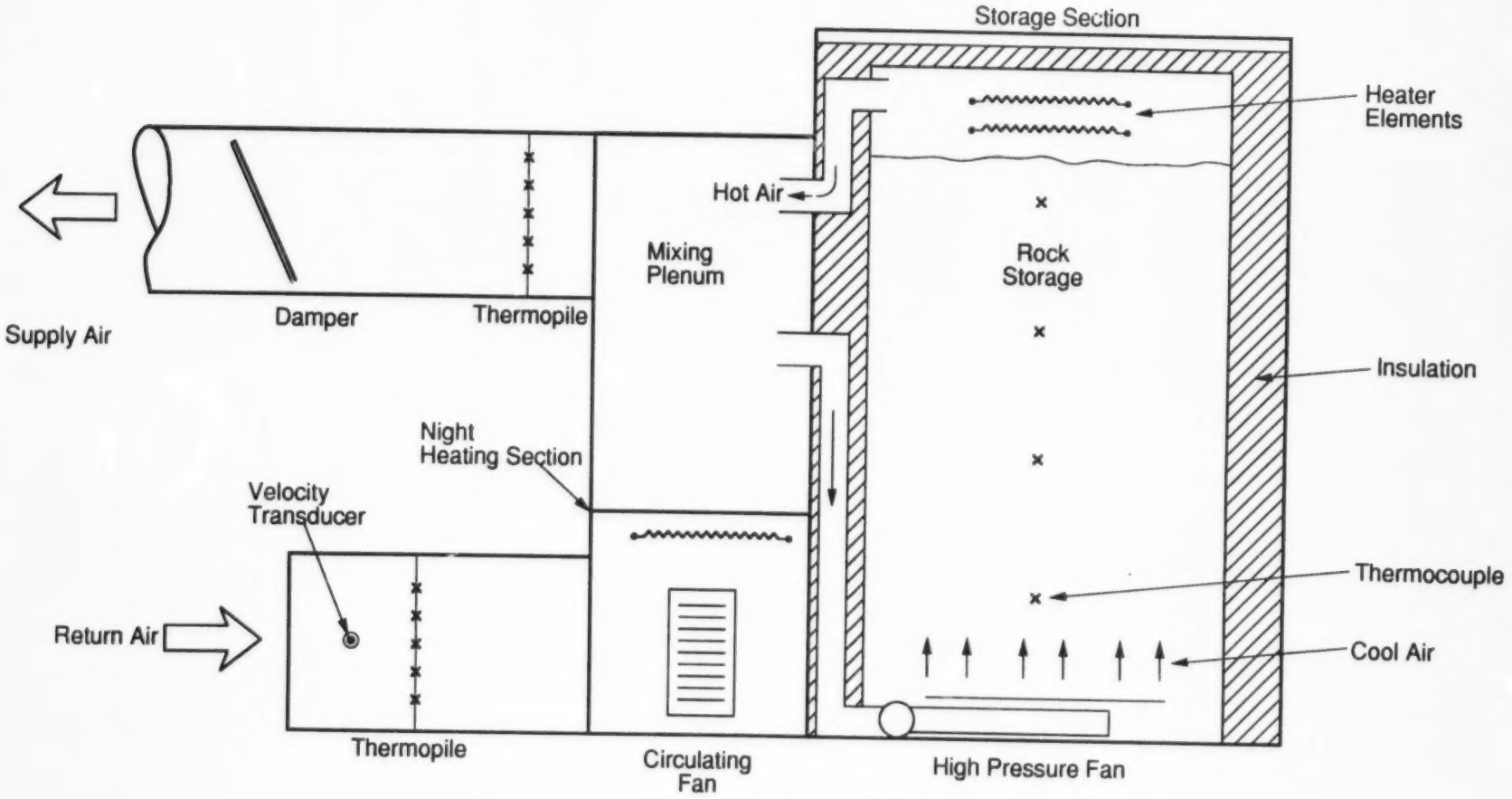

FIGURE A.1
CRUSHED - ROCK FURNACE
(Discharge Mode)

89-274
17972I-S16-RD

Ceramic Brick Furnace

The ceramic brick furnace uses high density bricks, having a high specific heat, as the storage medium. The operating temperature of the storage medium is 750 °C. The present furnace is a third generation design, based on earlier European models. The furnace consists of a storage section, and a fan/mixing plenum. The heating elements are located in the storage section. Figure A.2 shows a schematic of the furnace. Table A.2 lists the major characteristics of the ceramic brick furnace.

Table A.2
Ceramic Brick Furnace

height	1.80 m (71 in)
width	0.74 m (29 in)
weight of brick	795 kg (1750 lb)
footprint area	0.56 m^2 (6.04 ft^2)
nominal storage capacity	140 kWh
electrical input	24 kW

The ceramic brick furnace has two modes of operation. In the charge mode, 8, 16 or 24 kW of heater capacity, located in direct contact with the brick storage, are energized during the off-peak period. The amount of heater capacity is a function of the outdoor temperature and the storage temperature. The furnace charges for eight hours or until it is fully charged. Any heating required by the house during this period is obtained by withdrawing heat from storage.

In the discharge mode (on-peak) the cool air from the house is mixed with a small amount of air which has passed through the storage bricks. The amount of mixing air is controlled by a damper as a function of the supply air temperature. If additional heat is required during the on-peak period, which can not be supplied by the furnace, a manual reset (emergency heat) can be used to allow 8 kW of charging power to come on. The emergency heat cycle is turned off by the next off-peak signal from the utility.

During the 24-hour on-peak/off-peak cycle the operation of the circulating fan could either be continuous, at low speed, or thermostatically controlled by the house thermostat. The continuous fan operation mode is designed for homes with electronic air-cleaner or owners who prefer continuous air circulation in the house.

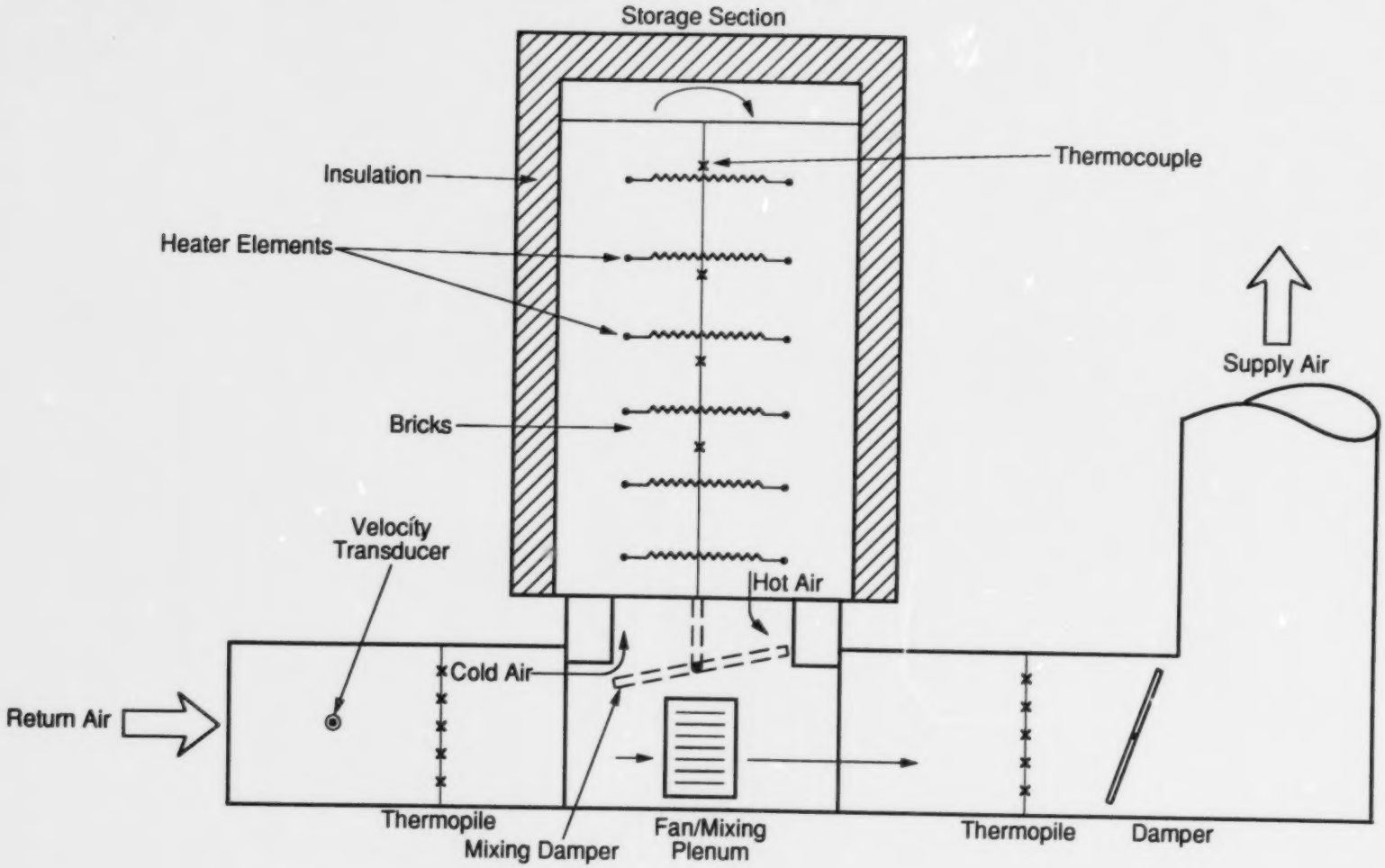

FIGURE A.2
CERAMIC - BRICK FURNACE
(Discharge Mode)

89-274 179722-S16-RD

APPENDIX B

Test Description

Test Program

Table B.1
Test Program

Standby loss test	-	without circulation fan
Standby loss test	-	with circulation fan
Charge/discharge	-	8 hours off-peak/16 hours on-peak
Safety Tests	-	high temperature limit
Surface Temperatures		

The standby tests measure the rate of energy loss from the furnace. When measured over time the standby loss is a measure of the inefficiency of the furnace. The comparison of the standby loss with and without the fan running determines the heat loss due to air leakage through the mixing damper and storage section. The standby tests were conducted with the furnace fully charged, to give maximum values.

The charge/discharge test is a simulation of the operation of a house heating system. The furnace is charged for eight hours off-peak, then discharged for 16 hours during the on-peak period. The thermostat is turned on for the entire 16 hours, indicating a demand for heat. Total heat delivered to the house is calculated, based on the mass flow of the air and the difference between the supply and return air temperatures. In addition, the overall furnace efficiency is determined.

The safety tests checked the performance of the high temperature limit switches and plenum temperature reset for over-temperature conditions. Surface temperatures were measured on the top sides of the furnace to determine the maximum surface operating temperature.

Crushed Rock Furnace

The furnace was instrumented with four J-type thermocouples in the storage chamber, a T-type thermopile across the supply and return ducts, and an air velocity transducer in the return air duct. Electrical energy input was measured with standard kilowatthour meters. The above measurements allowed for a simple control volume analysis of the furnace.

Ceramic Brick Furnace

The ceramic brick furnace was instrumented with four J-type thermocouples in the storage section, a thermopile across the supply and return air ducts, and an air velocity transducer in the return air duct. The test set-up was the same as for the crushed rock furnace.